# 9 Effects of Land Management Practices on Plant Invasions in Wildland Areas

Matthew L. Brooks

## 9.1 Introduction

The alteration of natural ecosystems by humans and anthropogenic dispersal of plant propagules beyond their native ranges have facilitated the dramatic spread and increase in dominance of nonnative plants worldwide since the late 1800s (Hobbs 2000; Mack et al. 2000). The amount of ecosystem alteration is related to predominant land uses, which can be summarized into four categories of increasing impact: (1) conservation – nature reserves, wilderness; (2) utilization – pastoralism, non-plantation silviculture, recreation; (3) replacement – cropping agriculture, plantation silviculture; and (4) removal – urbanization, mining, industrial development (Hobbs and Hopkins 1990; Hobbs 2000). The rate at which propagules are dispersed into new regions is largely related to the frequency and intensity of human activities, which generally covary with the degree of ecosystem alteration among the four land use categories.

Compared to areas where replacement or removal land uses are the norm, the management of plant invasions tends to be more complicated where conservation or utilization land uses prevail. The latter two land uses emphasize the need to maintain the integrity of natural ecosystems, whereas the former two do not require that natural ecosystem properties be maintained, and in some cases involve replacing them with simpler ecosystems (e.g., cropping monocultures). Options for controlling invading plants are more limited when their potential negative effects on native ecosystems may preclude their usage. This chapter is focused on conservation and utilization land uses that occur where native ecosystems are largely present and functioning, otherwise known as wildland areas.

Management plans for wildland areas typically focus on defining a balance between conservation and utilization, while maintaining ecosystem integrity in the process. Each land use type is associated with a range of land manage-

Ecological Studies, Vol. 193
W. Nentwig (Ed.)
Biological Invasions

ment practices designed to achieve particular objectives. It is not so much the land use itself that affects plant invasions, but rather the collective effects of all associated land management practices. For example, pastoralism is often associated with the practices of road building to facilitate access to rangelands and infrastructure (grazing allotments, watering sites, corrals), specific grazing methods (rotational, deferred), and forage improvement techniques (seeding, burning), all of which may be tailored for specific types of livestock (sheep, cattle, goats). Collectively, these practices have a net effect on the invasion potential of grazed landscapes, but individually they may have somewhat differing effects, and differing solutions tailored to their specific effects. In the field of pastoralism, the decisions that land managers typically face are generally not related to choosing between practicing, or not practicing livestock grazing, but rather to determining how to conduct livestock grazing in a manner that maximizes its sustainability and minimizes its potential negative effects on ecosystem integrity. Plant invasions are one of the key variables that can hinder the attainment of both these objectives.

In this chapter, I present a conceptual framework that can be used to evaluate the mechanisms by which land management practices affect plant invasions in wildland areas. I also discuss some of the measures that can be implemented to reduce the potential for invasion. Although the discussions and examples are limited to terrestrial ecosystems, the approach and principles presented in this chapter may be applied to other types of ecosystems as well.

## 9.2 Factors that Affect Plant Invasions

Factors that promote plant invasions are only generally understood. Many factors have been associated with the ability of nonnative plants to invade new areas, including various types of disturbance, connectivity to already invaded sites via pathways and vectors, disruption of large-scale ecological processes or regimes, loss of pollinators or other keystone species, and fluctuating resource levels (Hobbs and Huenneke 1992; D'Antonio 1993; Maron and Connors 1996; Lonsdale 1999; Davis et al. 2000). However, much of this research has produced contradictory results as to the primary factors that promote plant invasions (Lonsdale 1999; Williamson 1999).

The difficulty in finding clear and predictable patterns may be due to the episodic nature of plant invasions. This is not captured in most theoretical constructs, which tend to focus more on the inherent susceptibility of landscapes to invasion based on more fixed characteristics (species diversity, vegetation type, land use type). The susceptibility of landscapes to invasion can alternatively be viewed as fluctuating. In this case, invasions are most likely to occur during "windows of opportunity" when barriers that would otherwise prevent them are lowered (Johnstone1986). These barriers can be lowered and raised over time, alternatively opening and closing windows of opportunity for invasion. Barriers can be specific intrinsic characteristics affecting the "invasibility" (sensu Lonsdale 1999) of the landscape in question, or related to the extrinsic types and amounts of potential invader propagules. A thorough assessment of invasion potential must take into account both of these factors.

Davis et al. (2000) incorporated the concepts of variable opportunities for invasion into a theoretical model that assumes the invasion of landscapes by new species is affected by variations in (1) resource availability; (2) propagule availability; and (3) the types of species invading. These factors can be further grouped into the intrinsic property of resource availability, which is related to the availability of each type of potentially limiting resource (light, moisture, nitrogen, etc.), and the extrinsic property of propagule pressure, which includes the amount of each potentially invading species. Collectively, resource availability and propagule pressure affect invasion potential. The basic premise of this theory is that when and where the availability of otherwise limiting resources is high, landscapes are more invasible than when and where resources are low, but only if propagule pressure is sufficiently high and comprised of species well suited to colonize and establish new populations under prevailing environmental conditions (Fig. 9.1). Thus, the invasion potential of a landscape is highly contextual, as are the relative levels of resource availability and propagule pressure, which both vary over space and time.

Plant resource availability is a function of the underlying supply of light, water, and mineral nutrients, and the proportions of these resources that are unused by the existing vegetation. Resource availability can increase due to

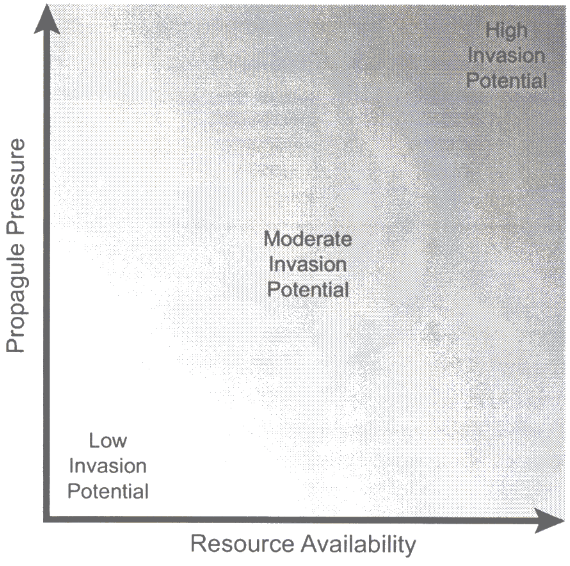


**Fig. 9.1** Invasion potential of landscapes is related to both resource availability and propagule pressure

direct additions to the landscape (atmospheric nitrogen deposition, agricultural fertilization) or increased rates of production within the landscape (nutrient cycling rates), or by reduced rates of uptake following declines in competition from extant plants after they are thinned or removed (Fig. 9.2, link A). The rate of resource uptake is inversely related to disturbance levels, because disturbance typically reduces vegetation biomass, thus reducing the amount of resources used. Established populations of nonnative plants can also feed back to affect resource supply. This can occur by direct increases in nutrient supply (nitrifying plants), or indirect increases brought about by inhibiting the growth of other species through competition (e.g., Brooks 2000) or inhibition (e.g., Callaway and Aschehoug 2000; Fig. 9.2, link C). Conversely, processes that reduce plant resource availability (e.g., increased plant productivity) may dampen invasion potential.

Propagule pressure is related to the number of propagules available to establish and increase populations. Propagules can be introduced deliberately (seeding projects or ornamental plants) or accidentally (adhering to vehicles or as contaminant in hay; Fig. 9.2, link B). Once established, populations of nonnative plants can promote their dominance by adding to their own pool of available propagules (Fig. 9.2, link D). Propagule pressure can be negatively affected by predators (granivores) or diseases that reduce the rate of production of new propagules. The types of propagules that are present are also an important factor. Species or functional groups of plants with properties that confer an advantage in colonizing and establishing populations under prevailing environmental conditions will be more successful than those lacking such properties.

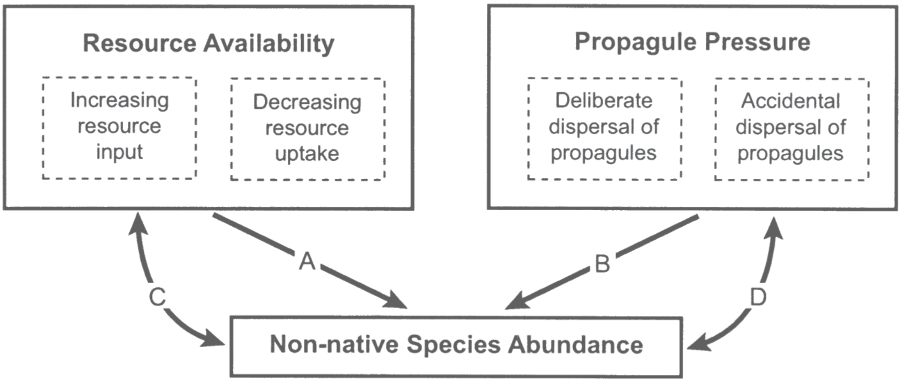


**Fig. 9.2** Relationships between resource availability, propagule pressure, and nonnative species abundance (modified from concepts presented in Davis et al. 2000). Resource availability (*A*) and propagule pressure (*B*) both affect the abundance of nonnative species populations. Once these populations become established, they can themselves affect resource availability (*C*) and propagule pressure (*D*)

## 9.3 Linking Land Management Practices with Invasion Potential

Much has been written about various aspects of plant invasions, but to date a universal approach to evaluating the relationships between land management practices and invasion potential by plants has not been explicitly described. The theoretical framework presented in Figs. 9.1 and 9.2 can be used for such a purpose. Specifically, this framework can be applied to any land management practice to evaluate links between invasion potential, resource availability, and propagule pressure, as well as specific management actions that may reduce the invasion potential of landscapes. The fluctuating and episodic dynamics of this theoretical framework is similar in nature to land management practices, which tend to also occur as punctuated activities.

There are a number of management actions that can target specific parts of the conceptual model presented in Fig. 9.2. For example, resource availability may be minimized by reducing the rate of resource input and/or increasing its rate of uptake. Similarly, propagule pressure may be minimized by reducing the rates of intentional and/or unintentional dispersal. The specific actions that will generate the most benefit will vary on a case-by-case basis, depending on the relative importance of resource supply and propagule pressure. This is important to understand, because costly efforts may otherwise be wasted on reducing resource availability when propagule pressure is relatively low (i.e., there are few propagules available to respond to resource fluctuations), or reducing propagule pressure when resource availability is limited (i.e., there are few resources for propagules to respond to).

An example is provided below that illustrates some of the ways that a land management practice – in this case, the management of vehicular routes – may increase the invasion potential of landscapes, and how these effects may be mitigated by specifically managing resource availability and propagule pressure.

### 9.3.1 Vehicular Route Management

Vehicular routes are perhaps the single, most pervasive land use feature in wildland areas worldwide. Approximately 6.3 million km of roads have been reported in the United States alone (National Research Council 1997), which vastly underestimates the actual amount of vehicular routes, due to extensive networks of unimproved routes and trails that remain uninventoried (Forman et al. 2003). The ecological effects of vehicular routes can range from physical and chemical changes of ecosystems to alterations in the population and community structure of organisms (Forman and Alexander 1998; Spellerberg 1998, 2002; Forman et al. 2003), including the spread and dominance of nonnative plants (Brooks and Lair 2007).

Vehicular routes can be classified into three general categories: off-highway vehicle trails and unimproved local roads, improved local roads and collector roads, and arterial roads and limited-access highways (Brooks and Lair 2007). Of these, off-highway vehicle trails and unimproved local roads characterize the typical routes encountered in wildland areas.

Vehicular routes are part of larger transportation infrastructures that some classify as a form of removal land use (e.g., Hobbs 2000). From this perspective, the immediate footprints of routes are recognized for their direct amelioration of local ecosystem properties (vegetation cover, soil hydrology). This has also been referred to as the direct local effect of vehicular routes (Fig. 9.3a; Brooks and Lair 2007). However, vehicular routes also have significant indirect and diffuse effects that encompass much larger areas, and do not impact local ecosystem processes as severely (Fig. 9.3a). These latter effects are of primary concern to managers of wildlands, since they threaten ecosystem structure and processes beyond route corridors. In addition, vehicular routes are integral to most other types of land uses. Anywhere people need to travel to conduct activities associated with various land uses, they usually travel by vehicle upon some sort of vehicular route.

The ecological effects of vehicular routes stem from both the vehicles themselves, and the surfaces created to facilitate their travel (Brooks and Lair 2007). Both can affect resource supply and propagule pressure of invading plants, although the management of each requires differing approaches.

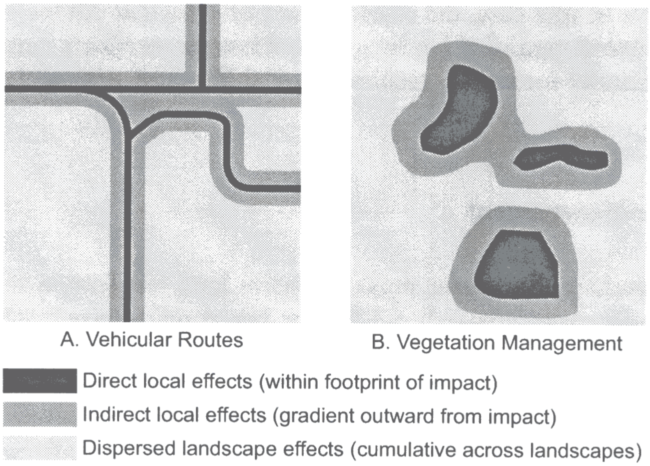


**Fig. 9.3a, b** Three primary scales of ecosystem impact of vehicular routes (**a**) and vegetation management treatments (**b**), modified from Brooks and Lair (2007)

#### 9.3.1.1 Vehicles

Vehicles produce atmospheric pollution in the form of nitrogen oxides and other compounds. At a regional scale, these pollutants can produce nitrogen deposition gradients that increase soil nitrogen levels (e.g., Padgett et al. 1999), and can lead to increased dominance by nonnative plants (Brooks 2003; Allen et al. 2007). At a local scale, they can create deposition gradients radiating outward from individual roads (e.g., Angold 1997). Unfortunately, the reduction of nitrogen deposition rates is outside the scope of what local land managers can typically influence – this can occur primarily through the efforts of regional air quality management districts or based on national automobile emission standards. To some degree, limitations on local rates of vehicular travel may reduce local deposition rates associated with individual roads. However, local land managers still should understand how broad-scale atmospheric nitrogen deposition may affect the processes of plant invasions into the wildland areas they manage. Such information may help them monitor more efficiently for the arrival of new plant invaders, and predict where these new invaders may reach levels that negatively affect ecosystem properties (e.g., fire regimes in deserts; Brooks 2003, Allen et al. 2007).

Vehicles can also serve as vectors for the unintentional dispersal of nonnative plant propagules (Clifford 1959; Schmidt 1989; Lonsdale and Lane 1994). Propagules may adhere directly to vehicles, or be blown along by wind currents created by vehicular travel. Maintenance guidelines for vehicles used by land managers may help reduce propagule pressure if they stipulate that vehicles be periodically washed, or at least washed when they are moved from one region to another. Vehicle washing is especially important after they have been operated in the vicinity of populations of nonnative plants that are high priorities for containment and control. Management of private vehicles used by people visiting a management unit is more problematic. Beyond relatively simple efforts to reduce dispersal rates by land management vehicles, it may be more efficient to focus resources on early detection and eradication of colonizing nonnative plants, rather than on extensive efforts to reduce their dispersal by private vehicles into a management unit (Lonsdale and Lane 1994).

#### 9.3.1.2 Vehicular Routes

Vehicular routes can have much greater effects on soil nutrient availability than do the vehicles themselves. For example, in arid and semi-arid environments, rainfall accumulation along roadsides can increase soil moisture levels, making conditions more conducive to plant growth (Brooks and Lair 2007). Even the tracks created by a single crossing of a motorcycle in desert soil can create microsites that facilitate the establishment and growth of nonnative plants, as demonstrated in the deserts of Kuwait (Brown and Schoknecht 2001) and in the Mojave Desert of North America (Davidson and Fox 1974; Brooks 2007).

The maintenance and engineering of roads can also significantly affect resource availability. Where vegetation is removed along roadside verges, reduced competition may increase resource availability (Vasek et al. 1975), and thus invasion potential. The creation of roadside berms can improve soil conditions, making it more suitable for the establishment and growth of nonnative species (Gelbard and Belnap 2003), especially if the conditions they create are significantly different from those of the surrounding landscape (Brooks 2007). The abundance of nonnative plants may also increase where new soils are introduced to create roadbeds, such as clay and limestone soils in an otherwise sandy landscape (Greenberg et al. 1997). Contouring to reduce the prominence of berms, and the use of roadbed materials that do not increase the relative fertility of the soil may help reduce rates of establishment by invading plant species. If the underlying fertility of roadsides cannot be reasonably managed, then regular vegetation management to maintain bare soil, and repeatedly remove new invaders as they become established, may be another option.

The construction and maintenance of vehicular routes can also significantly affect propagule pressure of invading species. Roadbed materials often originate from quarries that contain significant stands of invasive plants (M. Brooks, personal observations). In some cases, roadsides are recontoured and the materials redistributed elsewhere along other roadsides, potentially spreading nonnative plant propagules. The results of these activities often lead to new populations of plant invaders establishing in the vicinity of major road construction (M. Brooks, personal observations). Careful monitoring and control of nonnative plants at sites from which road materials originate is required to reduce the rates of propagule dispersal onto roadsides.

The verges of vehicle routes are often revegetated if plant cover has been lost during the course of construction or maintenance activities, especially if soil conservation or aesthetic degradation is of concern. Seedings are the most common revegetation method, and in many cases nonnative species are used. Nonnatives are often chosen simply because they have been used in the past and are part of institutionalized practices, but also because they are relatively inexpensive, compared to native seeds, and are often bred for high establishment and rapid growth rates. This last factor is of particular concern because selection for these traits also improves the chances that seeded species will spread beyond their points of application into wildland areas, and potentially become problems for land managers. Economic incentives are required to promote the development of native seed stocks, and research is needed to identify those native species that are most appropriate for specific vegetation types and ecoregions.

## 9.4 Managing Established Populations of Invasive Plants

Once plants have invaded and naturalized, control efforts involve treatments to remove, or at least reduce, their populations. In some cases, other species may be introduced through the process of revegetation to hinder the reestablishment of invading species after they are removed from an area. These practices are typical of the broader field of vegetation management, which transcends most realms of land management. For example, silviculturalists manage forests to maximize lumber production, and range conservationists manage rangelands to maximize livestock production. Fire managers manage vegetation before and after fires to manipulate fuelbed characteristics that affect fire behavior and fire regimes. Law enforcement and cultural resource managers may manage vegetation to respectively facilitate the detection of illegal activities and to maintain historically significant vegetation stands. Natural resource managers manage vegetation to create and maintain habitat for wildlife (forage and cover), reduce rates of soil erosion (species that stabilize soils), and promote certain plant community characteristics (high diversity, healthy populations of rare species). Vegetation management may also be targeted directly at eradicating or controlling the dominance of nonnative plants. All of these land management activities can affect invasion potential by influencing resource availability and propagule pressure. Even efforts to manage specific nonnative plants may unintentionally promote the subsequent invasion and rise to dominance of other nonnative species.

Just as vehicular routes can have ecosystem impacts at various spatial scales, so too can vegetation management treatments (Fig. 9.3b). Areas directly within the footprint of the treatments can have direct local effects that are very obvious, such as a clearcut in a forest. Invasive plants can dominate these areas where competition for light and soil resources has been temporarily reduced (Hobbs and Huenneke 1992). There may also be gradients of resource availability and propagule pressure extending outward from areas where vegetation has been removed, and which can affect landscape invasibility (Zink et al. 1995). The cumulative effect of multiple direct and indirect local effects can have diffuse landscape impacts that influence much broader areas.

### 9.4.1 Effects of Vegetation Management on Resource Availability

The removal of vegetation has obvious implications for resource availability to species that may subsequently invade. When plants are removed, there can be an immediate release from competition for soil nutrients and light, and when plants are revegetated, the opposite may occur. However, the different methods used to remove or add vegetation may have additional effects on nutrient availability that warrant further examination.

Fire is perhaps the oldest and most widely used tool for vegetation management worldwide. Its application requires only an ignition source, and appropriate fuelbed and weather conditions. Its effects on vegetation vary depending on the life history strategies and phenologic stages of the plants, and the intensity and duration of the fire. Continuous fires that have high intensity, long duration, and high percent fuel consumption result in significant removal of plant tissue that can increase resource availability by reducing plant competition (Fig. 9.4). Fires can also alter the chemistry of soils, increasing rates of nutrient input, as long as fire intensities are not excessively high, in which case nutrients may be volatilized and lost from the local landscape (DeBano et al. 1998).

Mechanical treatments can be targeted to either selectively remove all, or selectively thin a proportion, of an individual species or group of species

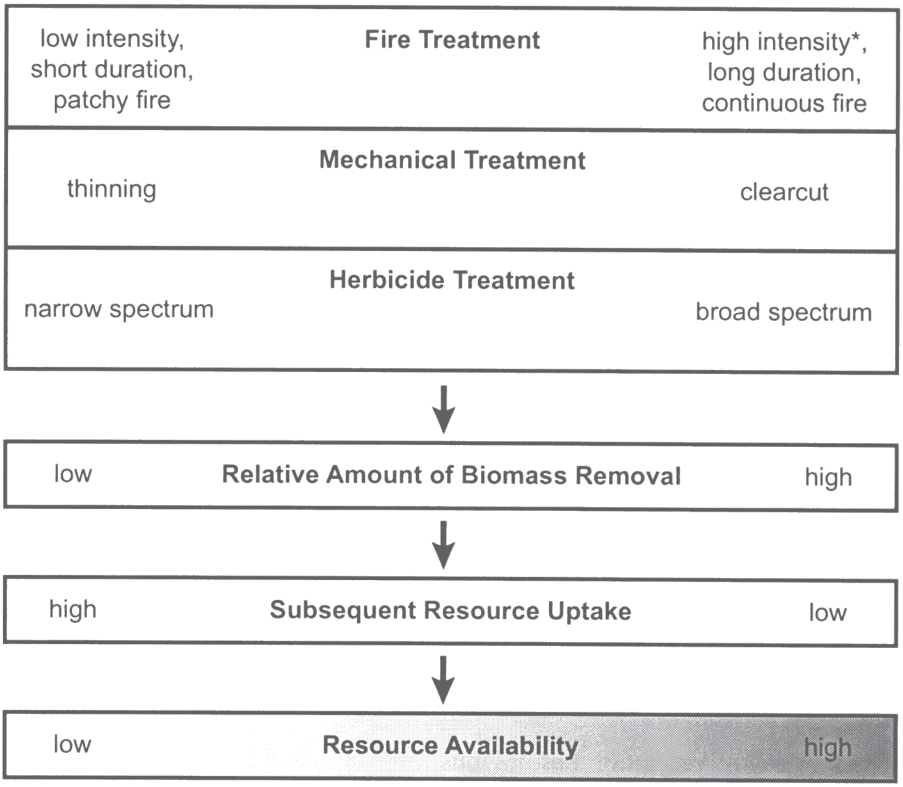


**Fig. 9.4** Relative effects of different types of fire, mechanical, and herbicide vegetation removal treatments on resource availability (* unless of very high intensity, in which case soil nutrients may be volatilized)

present at a site. Another approach involves removing the aboveground biomass of all plant species through clearcutting or blading. As the level of biomass removal increases, the rate of resource uptake declines, and the relative availability of resources increases (Fig. 9.4). However, mechanical treatments also typically cause significant soil disturbance, which can reduce soil fertility if subsequent erosion removes topsoil (Edeso et al. 1999), or increase soil fertility due to the decomposition of freshly removed plants (McLellan et al. 1995).

Herbicides are designed to either target a specific subset of plants (narrow spectrum), or target all or most plants (broad spectrum). The more species and biomass that are removed, the lower the resource uptake and the greater the resource availability. Herbicide treatments do not typically cause significant soil disturbance, although the decomposing plant material, especially the roots, can over time increase rates of nutrient input and potentially increase nutrient availability (McLellan et al. 1995).

In general, biomass reductions can be relatively transient if individual plants are not removed, but merely defoliated or thinned in the process of vegetation removal. Incomplete vegetation removal is most common with narrow-spectrum herbicides that target only specific suites of species (e.g., grasses), mechanical treatments that target specific life forms (e.g., forest understory thinning), and fires that only partially consume vegetation, or leave unburned islands within their perimeters. Biomass reductions can persist longer if whole plants are removed, and their replacements are slow to reestablish. Broad-spectrum herbicide treatments, mechanical treatments that completely remove plant biomass (e.g., bladed fuelbreaks), and fires with high intensity and long duration can all result in high rates of plant mortality.

The different techniques used for revegetation can also affect resource availability. In some cases, revegetation efforts include fertilization or mulching treatments that can increase resource supply, and may improve conditions for plant invasions. The benefits of these treatments for the establishing plants should be weighed against their effects on invasion potential. Seedings are typically used over large areas, especially after major disturbances such as fires or floods. If these treatments are applied aerially, then they have virtually no direct impact on the soil. However, if they are followed by tillage, or are applied with ground-based equipment, then significant soil disturbance may occur that could increase rates of nutrient mineralization. Again, the comparison of tillage vs. non-tillage seeding methods should include consideration for the potential effects of soil disturbance.

### 9.4.2 Effects of Vegetation Management on Propagule Pressure of Invaders

Any time humans, their mechanized equipment, or domesticated animals pass through a landscape, there is a chance they will disperse propagules of invading plants. All land management activities have this potential, although the degree to which they affect propagule pressure can be variable.

On its own, fire does not directly promote the dispersal of plant propagules. However, the management activities associated with fire, such as fuels management, fire suppression, and post-fire emergency stabilization, rehabilitation, and restoration activities, can increase propagule pressure by either accidentally or deliberately introducing propagules. By contrast, mechanical and herbicide treatments tend to involve significant travel throughout the landscape, which can facilitate plant dispersal. In many cases, herbicides are applied aerially, but in most cases in wildlands they are applied using a vehicle or on foot. In the latter case, there is the chance of spread of propagules as the applicators traverse the landscape. These impacts themselves may affect resource availability and propagule pressure. Efforts to mitigate these impacts may include ensuring that propagules are not adhering to people and equipment (this may require periodic decontamination), avoiding passage through known stands of invasives, and traversing the landscape in the most efficient manner (i.e., covering minimal ground).

### 9.4.3 Predicting the Effects of Vegetation Management Treatments

Vegetation removal is targeted at undesirable, often nonnative, species. Revegetation is focused on promoting the dominance of desirable species, which can target either nonnative or native species, or sometimes both. The factors that determine which species are undesirable and targeted for removal, and which are desirable and targeted for revegetation, depend on the desired effects of treatments that have their roots in broad management objectives. For example, if a plant invasion has altered fuelbed characteristics to the point that fire behavior and fire regimes are affected, creating an invasive plant/fire regime cycle (Brooks et al. 2004), then an important management objective may be to restore pre-invasion fuel and fire regime characteristics. This would involve removal of the undesirable species causing the fuelbed change, and possible revegetation of the desirable species that are necessary to restore the pre-invasion conditions. Unfortunately, it can be very difficult to predict if specific vegetation management treatments will have the effects necessary to achieve the desired management objective. In this example, fuelbed and fire regime characteristics are higher-order effects, with a number of intermediate steps and interactions that can lead to variable results (Fig. 9.5). Similar

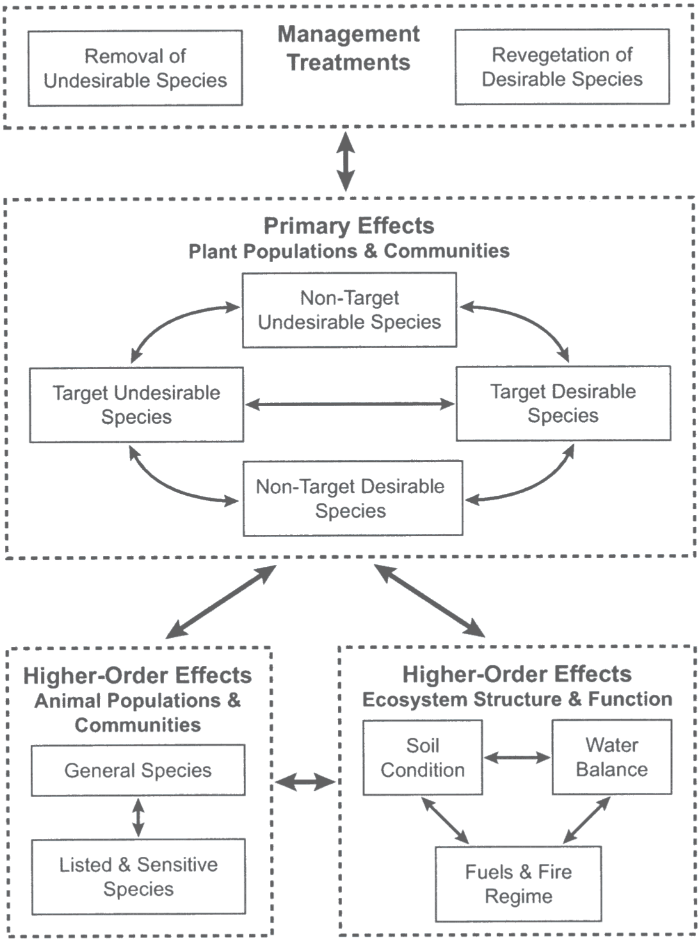


**Fig. 9.5** Conceptual model linking vegetation management treatments with primary and higher-order effects

difficulties may be encountered when vegetation management is prescribed to benefit other ecosystem properties, or populations of listed and sensitive wildlife species.

## 9.5 Conclusions

The processes that affect plant invasions can vary widely, so much so that unifying principles have been difficult to identify. The guidelines presented in this chapter focus on two factors, resource availability and propagule pressure, which can be used to provide a coarse-scale assessment of the invasion potential associated with any type of land management practice. More precise guidelines can likely be developed to evaluate specific management practices tailored for particular ecosystems, but it may be useful to use the framework presented in this chapter as a foundation to start from.

The issue of spatial scale associated with management treatments and invasion potential was only briefly discussed in this chapter, largely because most research has focused on the direct local and indirect local effects of land management practices (Fig. 9.3). The mechanisms and dynamics of dispersed landscape effects that result from multiple local impacts need to be better studied. Although specific management objectives may be focused on the invasion potential of specific places in the landscape, overarching management goals typically address the invasion potential of broad landscapes (e.g., nature reserves). Scientists should always strive to match the spatial scale of their studies with that of the information need they are addressing.

Some management actions are clearly more feasible than others, due to financial costs or other constraints. The framework presented in this chapter can help land managers identify the specific points at which plant invasions may most effectively be managed. Final decisions regarding where and when to apply specific actions will ultimately require another level of scrutiny that involves social, economic, logistical, and other factors that are beyond the scope of this chapter. However, this decision-making process should begin with biological concepts such as those presented here.

## References

Allen EB, Leela ER, Steers RJ, Bytnerowicz A, Fenn ME (2007) Impacts of atmospheric nitrogen deposition on Mojave Desert vegetation and soils. In: Webb RH, Fenstermaker LF, Heaton JS, Hughson DL, McDonald EV, Miller DM (eds) The Mojave Desert: ecosystem processes and sustainability. University of Arizona Press, Tucson (in press)

Angold PG (1997) The impact of roads on adjacent heathland vegetation: effects on plant species composition. J Appl Ecol 34:409–417

Brooks ML (2000) Competition between alien annual grasses and native annual plants in the Mojave Desert. Am Midl Nat 144:92–108

Brooks ML (2003) Effects of increased soil nitrogen on the dominance of alien annual plants in the Mojave Desert. J Appl Ecol 40:344–353

Brooks ML (2007) Spatial and temporal distribution of nonnative plants in the Mojave Desert. In: Webb RH, Fenstermaker LF, Heaton JS, Hughson DL, McDonald EV, Miller DM (eds) The Mojave Desert: ecosystem processes and sustainability. University of Arizona Press, Tucson (in press)

Brooks ML, Lair B (2007) Ecological effects of vehicular routes in a desert ecosystem. In: Webb RH, Fenstermaker LF, Heaton JS, Hughson DL, McDonald EV, Miller DM (eds) The Mojave Desert: ecosystem processes and sustainability. University of Arizona Press, Tucson (in press)

Brooks ML, D'Antonio CM, Richardson DM, Grace J, Keeley J, DiTomaso J, Hobbs R, Pellant M, Pyke D (2004) Effects of invasive alien plants on fire regimes. BioScience 54:677–688
Brown G, Schoknecht N (2001) Off-road vehicles and vegetation patterning in a degraded desert ecosystem in Kuwait. J Arid Environ 49:413–427
Callaway RM, Aschehoug ET (2000) Invasive plants versus their new and old neighbors: a mechanism for exotic invasion. Science 290:521–523
Clifford HT (1959) Seed dispersal by motor vehicles. J Ecol 47:311–315
D'Antonio CM (1993) Mechanisms controlling invasions of coastal plant communities by the alien succulent, *Carpobrotus edulis*. Ecology 74:83–95
Davidson E, Fox M (1974) Effects of off-road motorcycle activity on Mojave Desert vegetation and soil. Madroño 22:381–412
Davis MA, Grime PJ, Thompson K (2000) Fluctuating resources in plant communities: a general theory of invasibility. J Ecol 88:528–534
DeBano LF, Neary DG, Ffoliott PF (1998) Fire's effects on ecosystems. Wiley, New York
Edeso JM, Merino A, Gonzalez MJ, Marauri P (1999) Soil erosion under different harvesting managements in steep forestlands from northern Spain. Land Degrad Develop 10:79–88
Forman RTT, Alexander LE (1998) Roads and their major ecological effects. Annu Rev Ecol Syst 29:207–231
Forman RTT, Sperling D, Bissonette JA, Clevenger AP, Cutshall CD, Dale VH, Fahrig L, France R, Goldman CR, Heanue K, Jones JA, Swanson FJ, Turrentine T, Winter TC (2003) Road ecology: science and solutions. Island Press, Washington, DC
Gelbard JL, Belnap J (2003) Roads as conduits for exotic plant invasions in a semiarid landscape. Conserv Biol 17:420–432
Greenberg CH, Crownover SH, Gordon DR (1997) Roadside soil: a corridor for invasion in xeric scrub by nonindigenous plants. Nat Areas J 17:99–109
Hobbs RJ (2000) Land-use changes and invasions. In: Mooney HA, Hobbs RJ (eds) Invasive species in a changing world. Island Press, Washington, DC, pp 55–64
Hobbs RJ, Hopkins AJM (1990) From frontier to fragments: European impact on Australia's vegetation. Proc Ecol Soc Am 16:93–114
Hobbs RJ, Huenneke LF (1992) Disturbance, diversity and invasion: implications for conservation. Conserv Biol 6:324–337
Johnstone IM (1986) Plant invasion windows: a time-based classification of invasion potential. Biol Rev 61:369–394
Lonsdale WM (1999) Global patterns of plant invasions and the concept of invasibility. Ecology 80:1522–1536
Lonsdale WM, Lane AM (1994) Tourist vehicles as vectors of weed seeds in Kakadu National Park, Northern Australia. Biol Conserv 69:277–283
Mack RN, Simberloff D, Lonsdale WM, Evans H, Clout M, Bazzaz FA (2000) Biotic invasions: causes, epidemiology, global consequences, and control. Ecol Appl 10:689–710
Maron JL, Connors PG (1996) A native nitrogen-fixing shrub facilitates weed invasion. Oecologia 105:302–312
McLellan AJ, Fitter AH, Law R (1995) On decaying roots, mycorrhizal colonization, and the design of removal experiments. J Ecol 83:225–230
National Research Council (1997) Toward a sustainable future: addressing the long-term effects of motor vehicle transportation on climate and ecology. National Academy Press, Washington, DC
Padgett PE, Allen EB, Bytnerowicz A, Minnich RA (1999) Changes in soil inorganic nitrogen as related to atmospheric nitrogenous pollutants in southern California. Atmospheric Environ 33:769–781

Schmidt W (1989) Plant dispersal by motor cars. Vegetatio 80:147–152
Silveri A, Dunwiddie PW, Michaels HJ (2001) Logging and edaphic factors in the invasion of an Asian woody vine in a mesic North American forest. Biol Invasions 3:379–389
Spellerberg IF (1998) Ecological effects of roads and traffic: a literature review. Global Ecol Biogeogr Lett 7:317–333
Spellerberg IF (2002) Ecological effects of roads. Science Publishers, Plymouth
Vasek FC, Johnson HB, Brum GD (1975) Effects of power transmission lines on vegetation of the Mojave Desert. Madroño 23:114–130
Williamson M (1999) Invasions. Ecography 22:5–12
Zink TA, Allen MF, Heindl-Tenhunen B, Allen EB (1995) The effects of a disturbance corridor on and ecological reserve. Restor Ecol 3:304–310